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A study of the higher order Lamb resonances on elastic shells: their prediction and interpretation

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ABSTRACT

We study all the resonances generated on elastic shells for a ka from 0 to 500 for steel and aluminum for a thickness of 5%. We observe the lowest order symmetric and antisymmetric model or Lamb resonances, waterborne and pseudo-Stoneley resonances and the higher order Lamb modes A_i and S_i where $i=1, 2, 3 \ldots$. We plot some of the phase velocities of some of the relevant resonances out to a ka of 500 and indicate simple expressions that predict the onset of each of the resonances. We demonstrate by use of partial wave analysis that the new expressions that predict the onset (critical frequencies) of the higher order Lamb modes are reliable. Further, interesting phenomena occur at the inception of some of the resonances and we discuss some of those cases.

1. INTRODUCTION

The presence of resonances generated from acoustical signals impinging on submerged evacuated elastic shells has been known for some time. In particular, the presence of the symmetric or dilatational Lamb mode S_0 as well as the lowest order antisymmetric Lamb or Flexural mode A_0 are well know and frequently studied. Moreover, the existence of higher order symmetric S_i and antisymmetric A_i Lamb modes ($i>0$) manifest themselves with increasing frequency. In addition, newly studied phenomena such as pseudo-Stoneley resonances and pure waterborne waves have received attention recently.[1] All but the last phenomena have analogues for the infinite flat plate case which is fluid loaded on one side and evacuated on the other.

It is usual to associate resonances with vibrations, and the presence of the Lamb resonances on spherical shells can be associated with symmetric or antisymmetric vibrations that at discrete frequencies form standing waves on the object surface. These standing waves radiate into the fluid and add coherently with the specularly scattered signal producing a characteristic signature. The nature and appearance of the resonances just described are a function of material characteristics and shell thickness in addition to frequency. For very thin shells the lowest order resonance has a large amplitude and is in a region where there is a large recoil effect leading to both a large monopole term as well as the dipole term associated with the recoil effect. The subsequent symmetric Lamb modes are characterized by a sharp minimum followed by a sharp rise and then a return to a normal slowly varying back scattered return signal (form function). Flexural or antisymmetric resonances do not arise until the flexural phase velocity equals the speed of sound in the fluid (subsonic material waves are too heavily dampened to be observed); this value of frequency is referred to as coincidence frequency.[2-5] At and a little below coincidence frequency another phenomenon enters the picture, namely sharply defined waterborne waves which have their analogue in flat plates, namely Stoneley waves.[5] Thus, the resonances that arise from these waterborne waves are labeled pseudo-Stoneley resonances.[2, 5] They occur only in the frequency region about coincidence frequency and give rise to very sharp spikes superimposed on broadly overlapping flexural resonances. This effect can be very dramatic. Another dramatic effect arises from the S_1 symmetric resonance which is a separate topic presented at the 92 SPIE conference by Ali, Werby, and Gaunaurd.[6] Interestingly the onset of all of the higher order Lamb resonances can be obtained from the simple expressions used to predict the critical frequencies for the flat plate case. We will demonstrate this effect by employing the residual partial wave analysis (the partial wave component minus the exact acoustical background for a shell). It is only possible to perform the correct partial wave analysis if one has the correct background for the elastic shell. Thus we discuss it in the next section.

2. THE NEW ACOUSTIC BACKGROUND FOR SUBMERGED ELASTIC SHELLS

The rigid background concept for elastic solid targets in which the total elastic response is viewed as a superposition of a resonance response and a nonresonant acoustical background[1] (rigid for solid elastic targets) has proven quite successful as the "correct" background for elastic solids submerged in water. An analogous background for the elastic shell problem has proven more elusive to find. Earlier work[7] has shown that for very thin shells a soft background is useful in extracting the elastic residual, but for shells of greater thickness and at high frequencies, a rigid background has proven suitable. It has also been demonstrated that for some cases a soft background was suitable at the lower frequency limit and that a rigid background was suitable at the higher frequency limit for the same target. Here a model is outlined to describe acoustic scattering from an elastic shell in the absence of resonances. We then use it to better isolate resonances in the subsequent study.[9]

The inertial component of the radiation loading of a spherical shell at the surface is in the form:[8]

$$P_s = -i\omega \sum_{i=0}^{\infty} M_n W_n P_n^0(1) \,, \tag{1}$$

where $M_n = -\frac{\rho}{k} Im\left(i\,\frac{h_n(\mathrm{ka})}{h'_n(\mathrm{ka})}\right)$.

Here, M_n is the entrained mass per unit area for mode n, ω is the angular frequency, ρ the density of a fluid, P_n^0 (1) is an associated Legendre polynomial evaluated at 180 degrees, k is the wave number, and h_n is an outgoing spherical Hankel Function. Here W_n is an expansion coefficient related to the displacement potential. If we excite the sphere by an incident monochromatic plane wave, then we have

$$W_n = -i\omega\; a_n(\, j_n(\mathrm{ka}) + b_n h_n(\mathrm{ka}))\exp(-i\omega t)\,,$$

where j_n is a regular Bessel function and b_n is an unknown coefficient which corresponds to the partial wave scattering amplitude which we seek. Here, a_n is the plane wave expansion coefficient. The total pressure per unit area in the fluid due to the incident plane wave is

$$P_t = \frac{\rho c\,\omega}{\mathrm{ka}} \sum_{n=0}^{\infty} a_n \left(j_n(\mathrm{kr}) + b_n h_n(\mathrm{kr})\right) P_n^0(1)\exp(-i\omega t)\,. \tag{2}$$

The particle velocity at the surface of the object is:

$$v = \frac{-i}{\rho\omega k}\frac{\partial P_t}{\partial r}\,.$$

Here, c is the speed of sound in water. The particle acceleration α is the time derivative of v which leads to:

$$\alpha = -\frac{\omega^2}{\mathrm{ka}} \sum_{n=0}^{\infty} a_n \left(j'_n(\mathrm{kr}) + b_{nn}(\mathrm{kr})\,h'_n(\mathrm{kr})\right) P_n^0(1)\exp(-i\omega t)\,. \tag{3}$$

The force at the surface of the object due to the incident plane wave is, then, simply the product of the particle acceleration and the mass of the spherical shell. The mass of the spherical shell is $4\pi\rho_s a^3[1-(1-h)^3]/3$. Here h is the ratio of the shell thickness to the shell radius. The force due to the total fluid loading at the object surface is equal to the total inertial fluid loading times the surface area $4\pi a^2$ of the sphere. Here, a is the radius of the spherical shell and ρ_s is the density of the shell material. We equate these two forces to obtain the unknown coefficient b_n which leads to the following expression.

$$b_n = -\frac{\dfrac{3\rho}{\rho_s\left[1-(1-h)^3\right]}\ Im\left(i\,\dfrac{h_n(\mathrm{ka})}{h'_n(\mathrm{ka})}\right) j_n(\mathrm{ka}) - j'_n(\mathrm{ka})}{\dfrac{3\rho}{\rho_s\left[1-(1-h)^3\right]}\ Im\left(i\,\dfrac{h_n(\mathrm{ka})}{h'_n(\mathrm{ka})}\right) h_n(\mathrm{ka}) - h'_n(\mathrm{ka})}. \tag{4}$$

The scattered field for the new background is obtained by using the b_n's as the partial wave scattering amplitudes in a normal mode series. The b_n's define the new background and by subtracting this quantity from the elastic response, we obtain the residual response that reflects mainly the pure resonance contribution. It is easy to show that the imaginary part of the enclosed brackets in Eq. 4 is approximately equal to ka/(1+ka^2) so that for large ka, $b_n = -j'_n(\mathrm{ka})/h'_n(\mathrm{ka})$ which corresponds to a rigid scatterer and for both a very thin shell and at low frequency, $b_n = -j_n(\mathrm{ka})/h_n(\mathrm{ka})$ which corresponds to a soft scatterer. Thus we see that the background represented by Eq. 4 has the appropriate limits for thin shells at low frequencies (soft) as well as the appropriate limits for high frequencies (rigid).

2.1 The form functions for aluminum and steel for ka from 0 to 500

We illustrate in this section the form function for 5% thick Aluminum and Steel shells. Figure 1a–d represent backscatter from aluminum 1(a) from ka=0 to 250, 1(b) the residual results (with background subtracted) from 0 to 250, 1(c) for aluminum from 250 to 500, and 1(d) the residual for aluminum from 250 to 500. Figure 2a–d represent backscatter from steel 2(a) from ka=0 to 250, 2(b) the residual results from 0 to 250, 2(c) for steel from 250 to 500, and 2(d) the residual for steel from 250 to 500. It is clear that a great deal of detail is present in each of the plots. The low frequency large returns with the sharp spikes for both materials are due to a superposition of the pseudo-Stoneley resonances with the weaker broadly overlapping flexural resonances. The higher frequency resonances (about ka=250 in both cases) are due to the onset of the S_1 Lamb mode. We have indicated in the plots the onset of each of the modes.

2.2 Discussion of pure waterborne waves

We have earlier discussed pseudo-Stoneley waves. There is another phenomenon[10, 11] that corresponds to waves that have a phase velocity that is about the speed of sound in water. They are not, however, sharply defined in partial wave space, nor are they associated with the flexural wave or coincidence frequency. They are associated with the density of the material, and the thickness (really just the mass of the target) and the frequency. Their importance increases with frequency and they do not manifest themselves as sharp resonances in the form function but rather wash out other resonances such as S_0 and A_0 resonances. Thus for light material and thin shells such as aluminum and at high frequency one does not observe sharp resonances due to this wash out effect. We will not discuss this effect here.

2.3 A partial wave analysis

If one subtracts the correct background from the elastic response then by definition one is left with the "pure" resonance response. Resonances excited on bodies of canonical shape usually correspond to circumferentially excited waves which for spheres have a unique wave number. To be sure, this fact can be obscured by, for example, broadly overlapping partial waves; but none the less plotting the residual partial wave components–which is here referred to as a partial wave analysis–can be very revealing. There are two ways to perform a partial wave analysis: one can fix the mode number N and plot the residual response with respect to ka. On the other hand one can fix ka and plot the partial wave function with respect to mode number N. The first of these approaches is the most commonly used.

Figure 3a–c illustrates the PWA for 5% thick aluminum shells out to a ka of 500 for modes 1, 2, and 10. We have listed the onset of the different Lamb modes in Table 1 and indicated with arrows in the plots here the critical frequencies for each case. The same has been done for steel in Figure 4a–c. It is clear that the simple expressions listed in Table 1 and the computed values agree with the onset of the higher order Lamb modes.

2.4 Phase velocity plots

We have included in this work the phase velocities for the steel shell illustrated in Figure 5. Here we include the pseudo-Stoneley resonance (Fig. 5a), the pure waterborne wave (Fig. 5b), the A_0 resonance (Fig. 5c), the S_1 resonance (Fig. 5d), the A_1 resonance (Fig. 5e), the S_1 resonance (Fig. 5f), the S_2 resonance (Fig. 5g), the A_2 resonance (Fig. 5h), and the A_3 resonance (Fig. 5i). Note that the onset of each of the higher order Lamb resonances conforms to the values listed in Table 1. Further note that the S_1 resonance has a phase velocity that in effect decreases at some point (early on) then increases and then decreases again.

3. CONCLUSION

This is only a preliminary study of a large ongoing study of Lamb resonances. It is encouraging that most effects are easily understood in terms of flat plate theory and that the critical frequencies can be predicted by such simple expressions. Further some of the more dramatic effects such as the pseudo-Stoneley resonances[2–5] and those due to the S_1 resonance[6, 11] can be interpreted.

4. ACKNOWLEDGMENTS

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ALUMINUM		STEEL	
A_1	129.3	A_1	140.2
S_1	258.5	S_1	243.9
S_2	269.1	S_2	280.3
A_2	387.8	A_2	420.5
A_3	4[illegible].7	A_3	487.9
S_3	517.1	S_3	560.6
S_4	538.2	S_4	731.9

Table 1. Critical frequencies for the higher order Lamb modes ka=$\pi(v_s/v_w)n/h$ A when n odd S when n even, ka=$\pi(v_L/v_w)$ n/h S when n odd A when n even h is % thickness of shell.

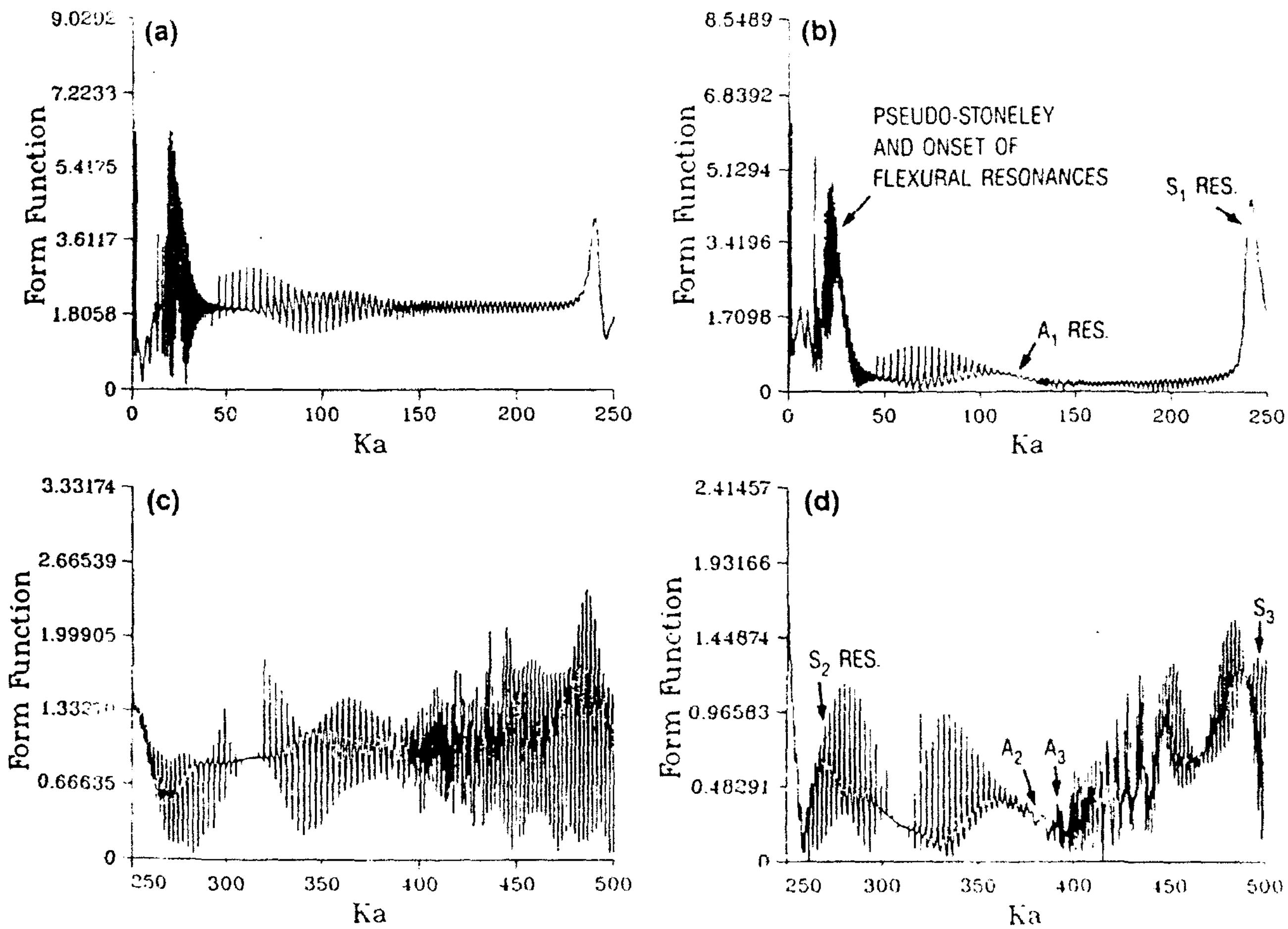

Fig. 1. (a) Backscatter from 5% aluminum shell from ka = 0 to 250; (b) residual backscatter for case Ia; (c) backscatter from 5% aluminum shell from ka = 250 to 500; and (d) residual backscatter for case Ic.

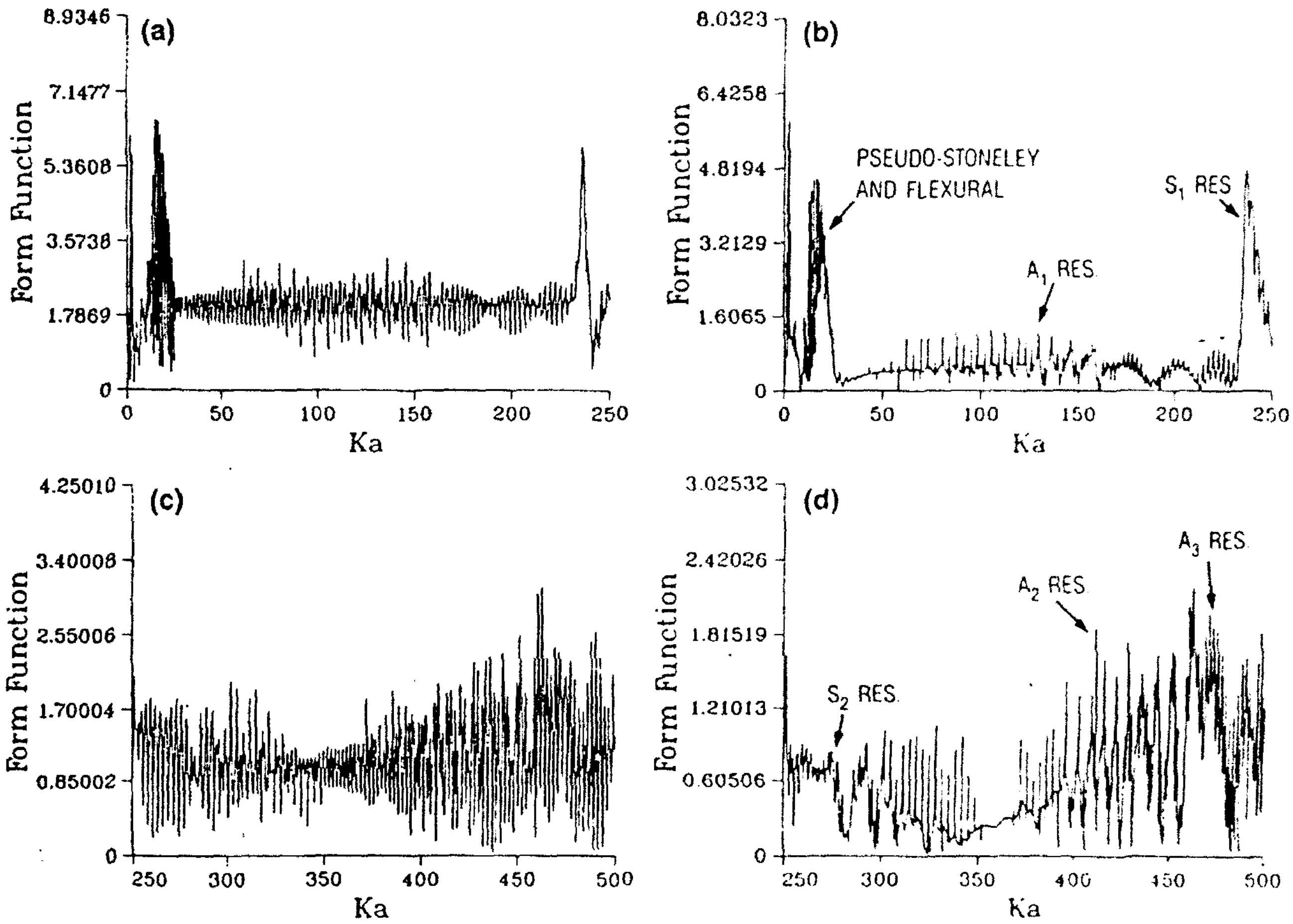

Fig. 2. (a) Backscatter from 5% steel shell from ka = 0 to 250; (b) residual backscatte. for case la; (c) backscatter from 5% steel shell from ka = 250 to 500; and (d) residual backscatter for case lc.

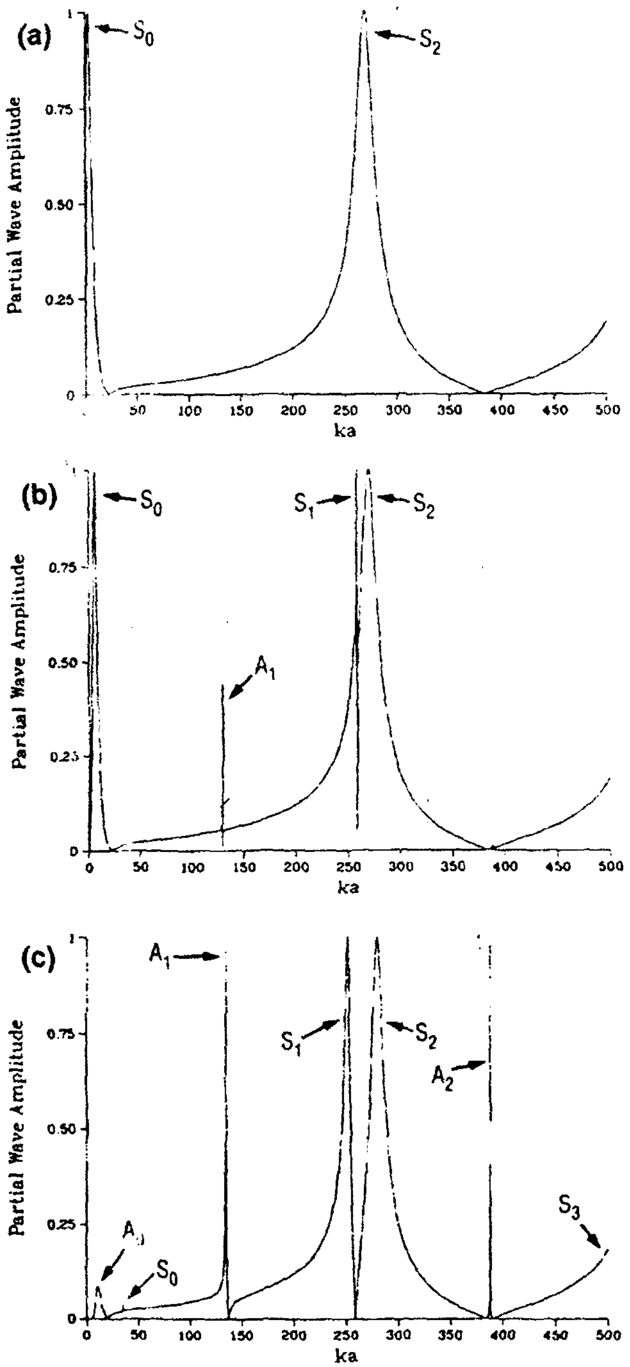

Fig. 3. Partial wave for aluminum: (a) mode 1, (b) mode 2, and (c) mode 10.

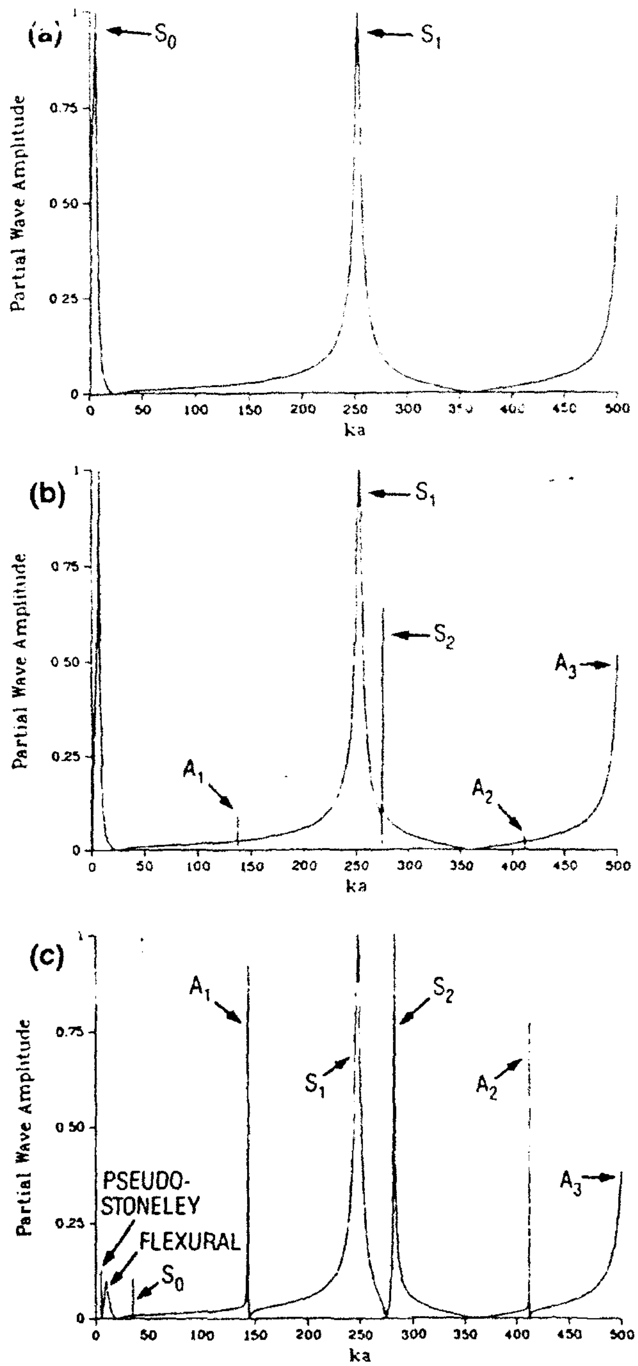

Fig. 4. Partial wave for steel: (a) mode 1, (b) mode 2, and (c) mode 10.

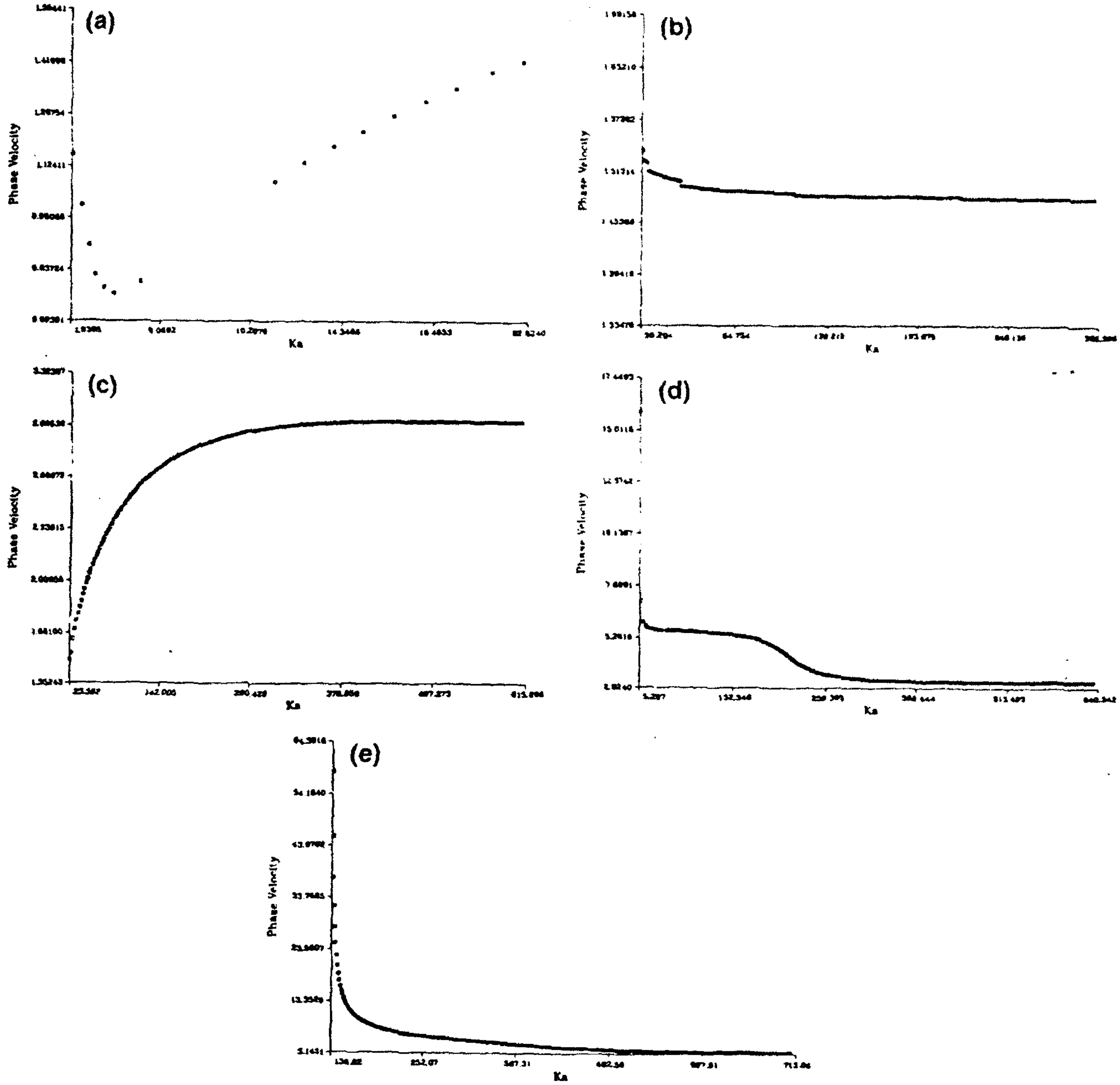

Fig. 5. Phase velocity for steel: (a) pseudo-Stoneley resonance, 5% steel: (b) waterborne wave; (c) A_0 resonance; (d) S_0 resonance; (e) A_1 resonance.

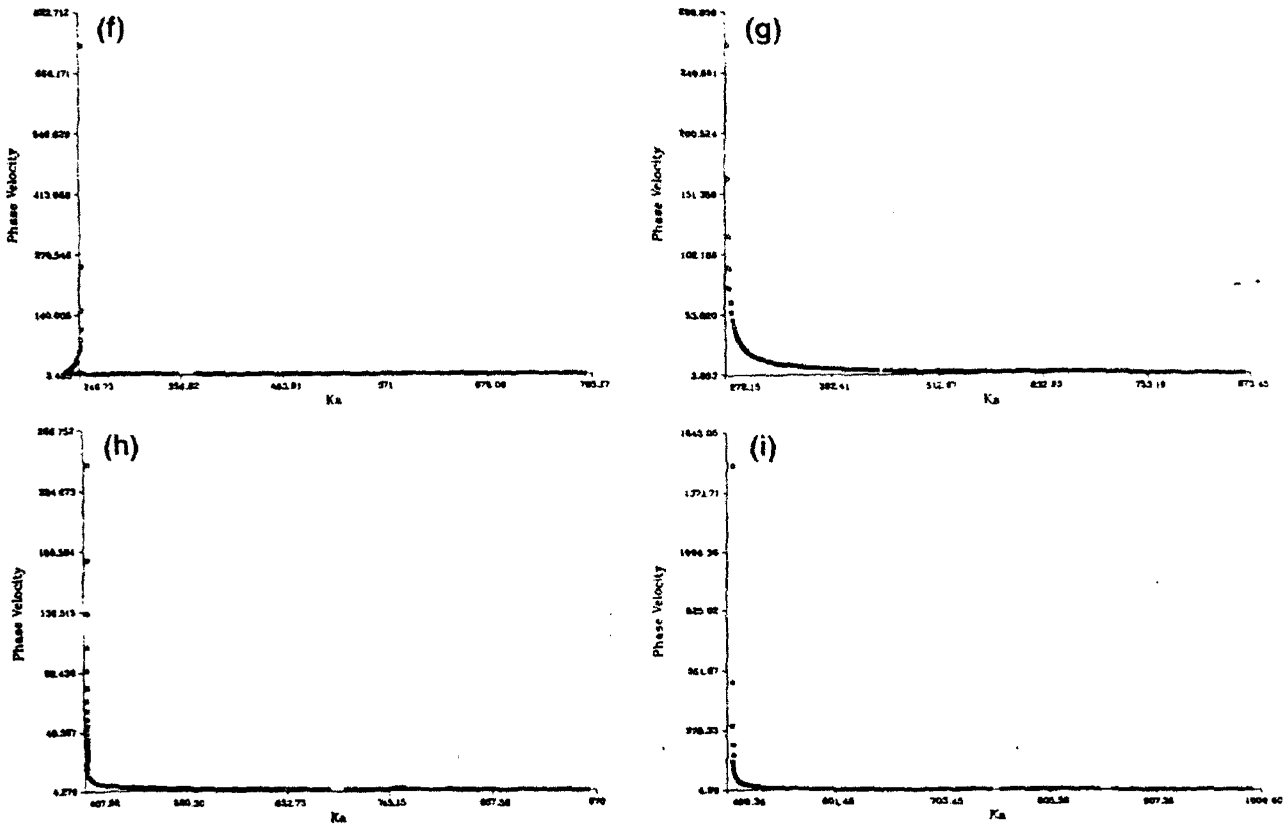

Fig. 5. Phase velocity for steel (cont.) (f) S_1 resonance; (g) S_2 resonance; (h) A_2 resonance; and (i) A_3 resonance.